(8) A cliff stabilization project for the Scarborough Bluffs (east of Toronto on Lake Ontario) is discussed by Parker, Matich, and Denney (1986) (Figure III-5-24). It has been recognized that arresting the foreshore downcutting at the base of the bluffs is not sufficient on its own to control the erosion of an oversteep slope; proper drainage systems must be implemented to prevent gullies from developing and to address the problem of piping through sand and silt lenses. Parker, Matich, and Denney (1986) also note that the toe of the bluff must be surcharged in some locations to prevent large slip failures from occurring. One function of the land base created at the toe of the slope in Figure III-5-24 is to provide sufficient area to construct a surcharge berm. The surcharge provided by extensive shingle beaches along the south coast of England is known to contribute to the stability of cliffs that rise behind the beaches (Fleming and Summers 1986).

Figure III-5-24. Shore protection consisting of a wide berm protected by a revetment along the base of the Scarborough Bluffs located east of Toronto on Lake Ontario

Bioegineering, which consists of promoting the growth of vegetation (e.g., through the placement of mats consisting of bundled twigs to enhance rooting), may also help to stabilize an oversteep slope.

(9) Another extensive review of subaerial processes was made by Hutchinson (1986); other processes that he identified included: freeze/thaw cycles; alternate wetting and drying; and mechanical and hydrodynamic effects of micro-geological features such as erratic cobbles and boring organisms. Hutchinson (1986) provides sample test results indicating that seawater penetrated the pores of glacial tills from the Holderness coast of England (along the North Sea) to depths of at least 0.85 m. He goes on to suggest that an increase in the concentration of NaCl in the pore water from the intrusion of the seawater may increase the net attractive forces between clay particles and increase the degree of aggregation. The degree to which this effect will occur will depend on the clay content and the chemical properties of the cohesive sediment. Hutchinson (1986) concludes that the opposite effect may occur along freshwater shores, where the intrusion of fresh water may dilute the salt or cation content, thus decreasing the net attractive forces between clay particles, and increasing the susceptibility to erosion.

III-5-8. Transport Processes

a. Advection and dispersion.

(1) Cohesive sediments are not transported as bed load, except in the form of fluid mud (see Part III-5-8b below). They almost always are transported in suspension: advected (carried with the ambient water at the flow velocity) and dispersed (moved from areas of high sediment concentration to low by mixing, such as turbulence). Advection and dispersion are described in Part II-6-2.

(2) But sediment, even a floc, is denser than the ambient water and hence settles as it is being advected and dispersed. This results in a downward bias of the vertical dispersion relation

$$S - Cw = -D_z \frac{dC}{dz} \tag{III-5-3}$$

where

S = vertical (upward) dispersion of sediment, kg/m^2/sec (lb/ft^2/sec)

w = settling velocity of floc, m/sec (ft/sec)

D_z = vertical dispersion coefficient, m^2/s (ft^2/sec)

C = suspended sediment concentration, kg/m^3 (lb/ft^3)

z = vertical dimension, m (ft)

b. Fluid mud. Fluid mud, as its name suggests, flows and is a mechanism for transport of cohesive sediment. It flows down slopes by gravity, sometimes referred to as a 'turbidity current,' which is why fluid mud is often found in the bottoms of dredged cuts. Fluid mud is also dragged along by the shear of the water flowing above it. How it flows is determined by its rheology; which in turn, must be measured for each fluid mud combination of sediment and water. Fluid mud may have an apparent yield point, remaining stable until a critical slope or shear is exceeded. More likely, its flow velocity will vary in a nonlinear way with slope or shear, from stiffest at lowest shear to most fluid at highest shear.

III-5-9. Deposition Processes

a. Flocculation.

(1) Cohesive sediments rarely settle as individual grains in nature. Collisions between sediment grains are encouraged by differences in settling velocity, turbulence, Brownian motion, and electrochemical attraction or cohesion.

(2) When cohesive grains collide they tend to stick together, or cohere. To determine settling velocity in the laboratory, cohesive grains can be kept apart in distilled water containing a dispersing agent to neutralize the electrochemical bond.

(3) The process by which individual cohesive particles agglomerate while settling is called *flocculation*; and the resulting large particles with entrapped water, *flocs*. The settling velocity of a floc is a function of its size, shape, and relative density. A floc usually settles faster than its constituent particles; but because of

the entrapped water, its density is less than that of the sediment mineral, and the settling velocity of the floc may actually be slower than that of an individual clay particle. The size and shape of flocs, and their settling velocity, are hydrodynamic sediment properties which must be measured or determined by model calibration as described in Part III-5-3.

b. Shear stress. The principle of excess shear is also used for correlating observed rates of cohesive sediment deposition with flow. But for deposition, 'excess' is the amount by which the shear τ is less than a critical shear for deposition τ_s.

c. Krone Equation. The Krone Equation for mud deposition (Krone 1962, Mehta et al. 1989) is as follows:

$$\frac{dm}{dt} = Cw\frac{(\tau_s - \tau)}{\tau_s} \tag{III-5-4}$$

where

m = mass of sediment on the bed, kg/m^2 (lb/ft^2)

t = time, sec

τ = bed shear, Pa (lbf/ft^2)

τ_s = critical shear for deposition, Pa (lbf/ft^2)

C = suspended sediment concentration above the bed, kg/m^3 (lb/ft^3)

w = settling velocity of sediment floc, m/sec (ft/sec)

Comparison of the Krone and Parthenaides Equations (Part III-5-4d) suggests that the Krone Equation may be less empirical, more theoretical. There is no obvious empirical coefficient to match the Parthenaides coefficient M_p, but the unknown coefficient hidden in the Krone Equation is w, the settling velocity of the flocs.

d. Fluid mud. Deposition takes place at both interfaces: that between water and fluid mud; and also that between fluid mud and the stationary bed. At the water/fluid mud interface, the process can still be predicted by the Krone Equation, except the density of the deposited sediment is less than 1,100 to 1,200 kg/m^3 (70 to 75 lb/ft^3). At the fluid mud/bed interface, the deposition process is one of consolidation: as the fluid mud drains, it consolidates to the point where it is too dense to remain fluid.

III-5-10. Consolidation

a. Strength versus consolidation.

(1) The critical shear for erosion τ_c is a function of the consolidation or density of the bed. Think of the cohesion between sediment particles varying inversely, like the force of gravity, with distance between particles. The closer the particles are to each other, the stronger the cohesive bond and the greater the shear force needed to separate them.

(2) The Migniot Equation expresses the exponential relationship between mud density and critical shear for erosion as:

$$\tau_c = N \rho_s^M \tag{III-5-5}$$

where

ρ_s = bulk density of sediment on the surface of the bed, kg/m^3 (lb/ft^3)

M, N = constants to be determined for the sediment and water.
M is dimensionless and tends to be less than 1; N equals 10^{-1} or 10^{-2} in the SI system of units.

b. Degree of consolidation. The Terzaghi consolidation relation, developed for building settlement calculations, also serves to illustrate the consolidation of coastal cohesive sediment.

$$u = 0.964 \left(\frac{tC_v}{P^2} \right)^{0.415} \tag{III-5-6}$$

where

u = degree of consolidation, dimensionless ratio

C_v = a consolidation coefficient to be determined, m^2/sec (ft^2/sec) (values on the order of 1 x 10-5 m^2/sec are not uncommon)

P = length of the drainage path, m (ft) (generally depth of burial)

III-5-11. Wave Propagation

a. Roughness and shear.

(1) The predominant nearshore wave transformation associated with muddy beds is wave energy dissipation or attenuation. Refraction, diffraction, and reflection all pretty much obey the rules set out in Part II-3-3, but wave attenuation is generally much greater over mud beaches than over sand and gravel. As more wave energy is absorbed by the mud, less reaches the breaker line.

(2) This energy dissipation can only partially be accounted for through the traditional mechanisms of bed roughness and friction. In fact, a mud bed is usually smoother (less rough) than sand.

b. Fluid mud.

(1) The predominant mechanism of wave attenuation is in the thick, viscous boundary layer of fluid mud (Lee 1995, Lee and Mehta 1994). Part of the wave energy goes to ‘pumping up’ excess pore pressures maintaining the mud in a fluid state. But more is converted to work done in moving the fluid mud against viscous shear.

Example Problem III-5-1

FIND:

Apply the Parthenaides and Krone Equations to the annular flume test results in the table, to determine values of:

M_p = Parthenaides coefficient for this combination of sediment and water

τ_c = Critical shear for erosion at this sediment density

w = Settling velocity of sediment flocs for this combination of sediment and water

τ_s = Critical shear for deposition for this combination of sediment and water

For the purposes of this example, ignore changes in bed elevation and water depth due to erosion and deposition.

GIVEN:

Table III-5-2
Example Problem III-5-1, "Annular Flume Test Results"

Applied Shear (Pa)	Duration (sec)	Starting Concentration (kg/m^3)	End Concentration (kg/m^3)
0	600	0	0
0.2	600	0	0
0.4	600	0	0
0.6	600	0	1
0.8	600	1	3.33
1.0	600	3.33	7
0.8	600	7	7
0.6	600	7	7
0.4	600	7	7
0.2	600	7	1
0	50	1	0

Bulk (dry) density of sediment on the bed = 1,500 kg/m^3

Water density = 1,020 kg/m^3

Area of annular flume bed = 1 m^2

Water depth = 0.2 m

Total water volume, therefore = 0.2 m^3

(Sheet 1 of 3)

Example Problem III-5-1 (Continued)

SOLUTION:

Since the bed area of the annular flume has been carefully chosen to be 1 m^2, the rate of change of total sediment suspension will directly give us the quantity dm_b/dt. Otherwise, we would have had to multiply both sides of both equations by the area of the bed.

Our results are not given as total sediment in suspension, but as concentration in kg/m^3. We need to multiply them by the volume of water in the annular flume, 0.2 m^3, to get total sediment numbers equivalent to dm/dt on the bed.

So, for example, when the applied shear was 0.6 Pa

$$dm/dt = (V \times \Delta C) / (A \times \Delta T) = (0.2\ m^3 \times -1\ kg/m^3) / (1\ m^2 \times 600\ sec)$$

$$= -3.33 \times 10^{-4}\ kg/m^2\text{-sec}$$

Similarly for 0.8 Pa, -7.77×10^{-4} $kg/m^2/sec$, and for 1.0 Pa, -1.22×10^{-3} kg/m^2-sec.

This concludes the erosion data for the Parthenaides Equation. By plotting erosion rate versus shear (Figure III-5-25), we can extrapolate back to the shear at which the erosion rate is zero, $\tau_c =$ 0.45 Pa. From the same plot we can read M_p, the erosion rate at $2\tau_c = 0.9$ Pa, = 10^{-3} kg/m^2-sec.

In the same way, the deposition results can be used as shear is reduced, with the Krone Equation for

0.2 Pa and $C_{avg} =$ 4.0 kg/m^3, dm/dt = 2×10^{-3} kg/m^2-sec

and for

0.0 Pa and 0.5 kg/m^3, dm/dt = 4×10^{-3} kg/m^2-sec

Note that we can use the mean sediment concentration C_{avg}, since deposition rate is a linear function of concentration. In high concentration, settling velocity also becomes an inverse function of concentration.

The result at 0.0 Pa gives the floc settling velocity directly

$$w = (dm/dt) / (C_{avg} \times \tau_s / \tau_s) = (4 \times 10^{-3}\ kg/m^2\text{-sec}) / (0.5\ kg/m^3) = 8 \times 10^{-3}\ m/sec$$

Substituting this in the Krone Equation at 0.2 Pa, yields

$$\tau_s = (\tau \times C_{avg} \times w) / (C_{avg} \times w - dm/dt)$$

$$= (0.2\ Pa \times 4.0\ kg/m^3 \times 8 \times 10^{-3}\ m/sec) / (4.0\ kg/m^3 \times 8 \times 10^{-3}\ m/sec - 2 \times 10^{-3}\ kg/m^2\text{-sec})$$

$$= 0.21\ Pa$$

A real set of data, whether from field or laboratory annular flume, will be more difficult to work with. Complications to be expected are:

The variation of erosion rate with bed shear will not be linear, but will require some judgment and nonlinear regression to determine τ_c.

(Sheet 2 of 3)